Production of J/ψ and Υ mesons in proton-lead collisions at $\sqrt{s_{NN}} = 5\ \mathrm{TeV}$

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Outline

- The LHCb detector and pPb data taking
- Physics motivation
- J/ψ production and nuclear effects in pPb at 5 TeV

  [JHEP 02 (2013) 072]
- $\Upsilon(nS)$ production and nuclear effects in pPb at 5 TeV

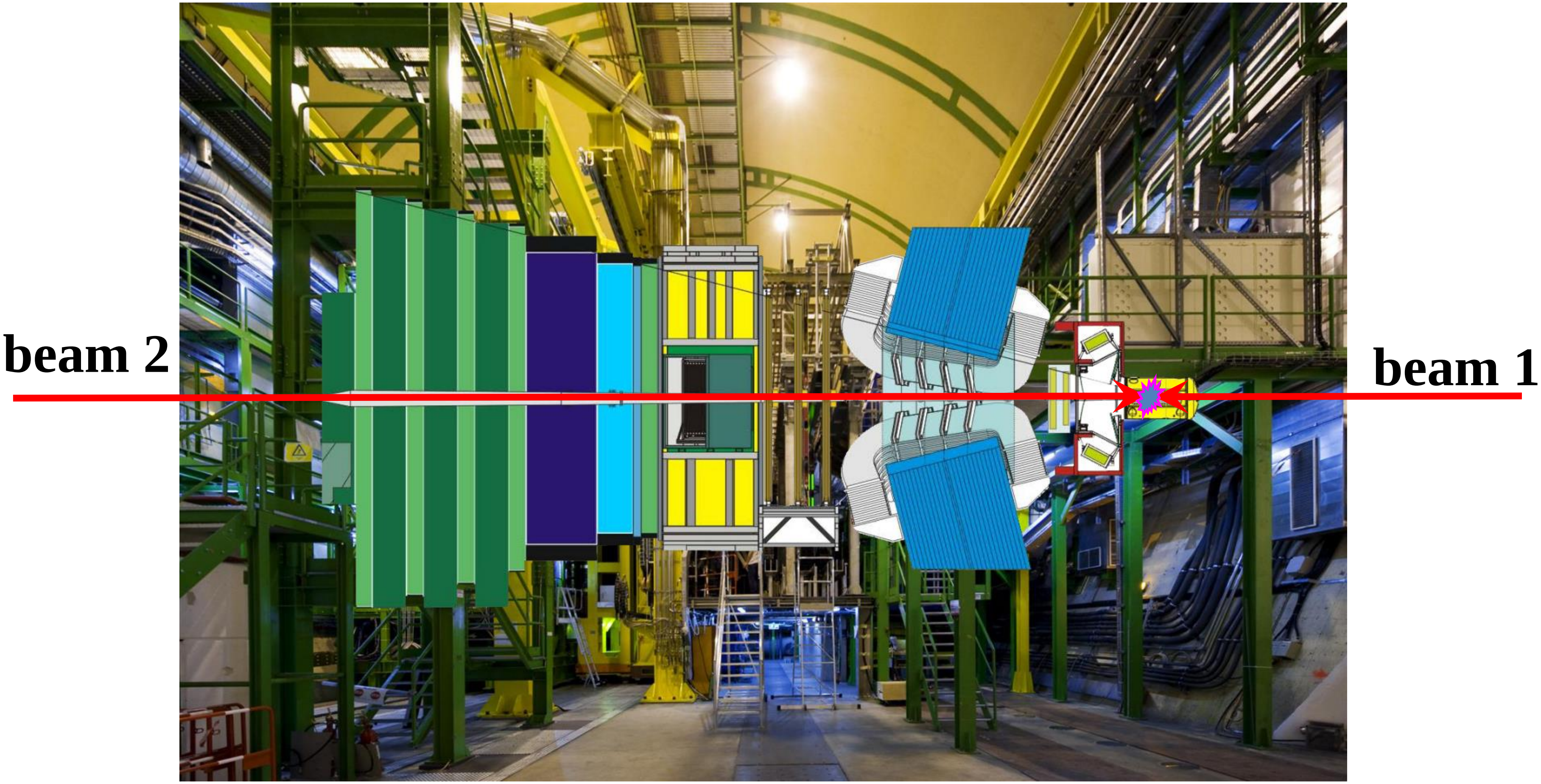
  [arXiv:1405.5152] NEW!
- Summary and prospects

LHCb detector

JINST 3 (2008) S08005

Dedicated to beauty and charm physics

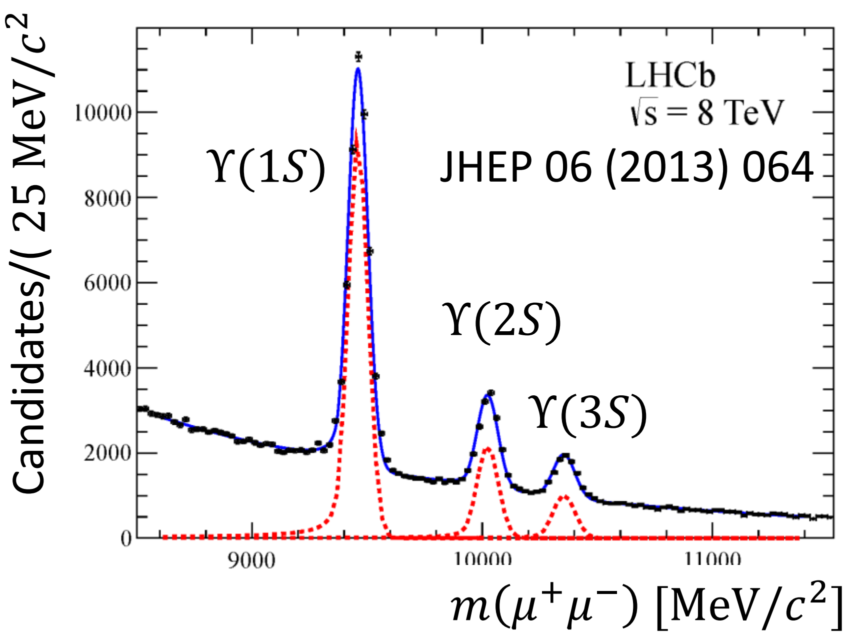
Pseudorapidity acceptance
$2 < \eta < 5$

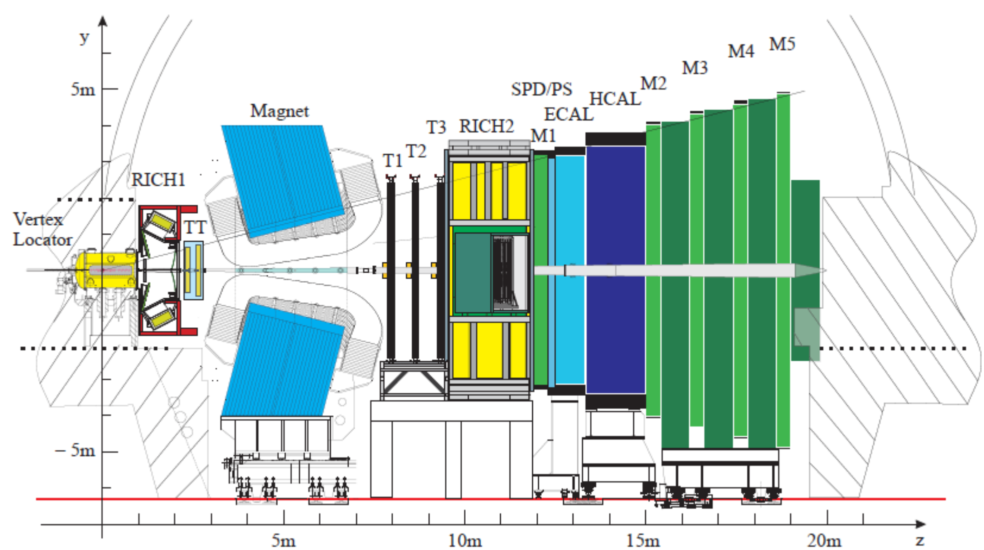


can also contribute to heavy-ion physics …

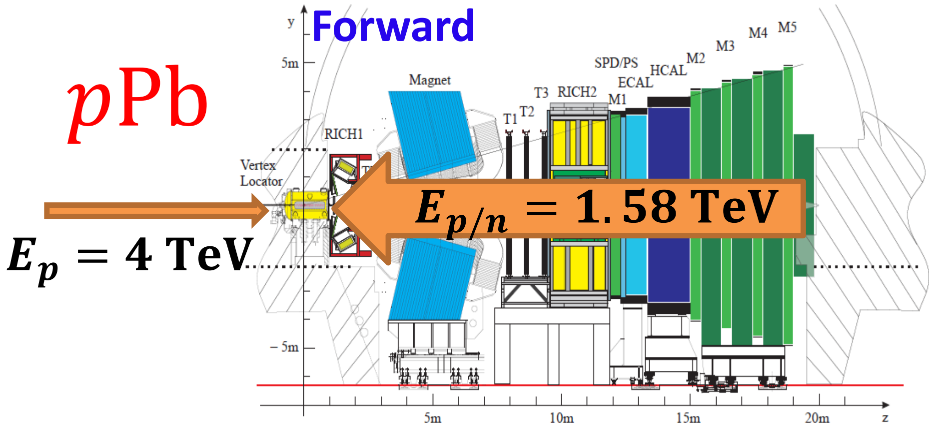
LHCb in a nutshell

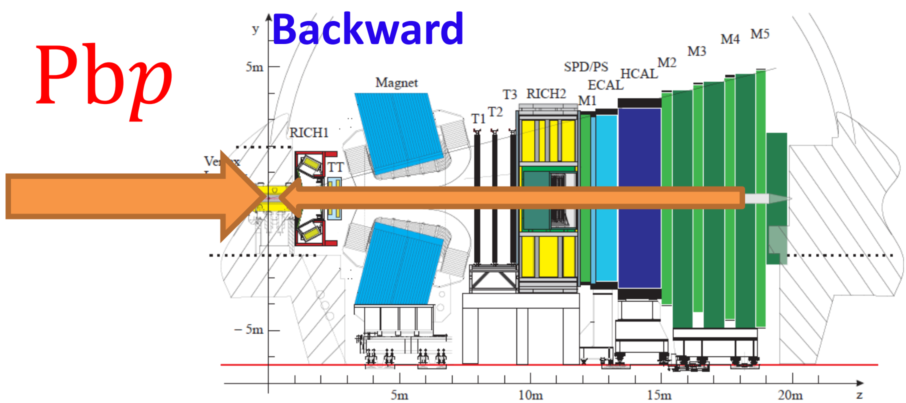
Impact parameter:	$\sigma_{IP} = 20\ \mu\text{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \text{GeV}/c)$
Mass :	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $\text{m}_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$





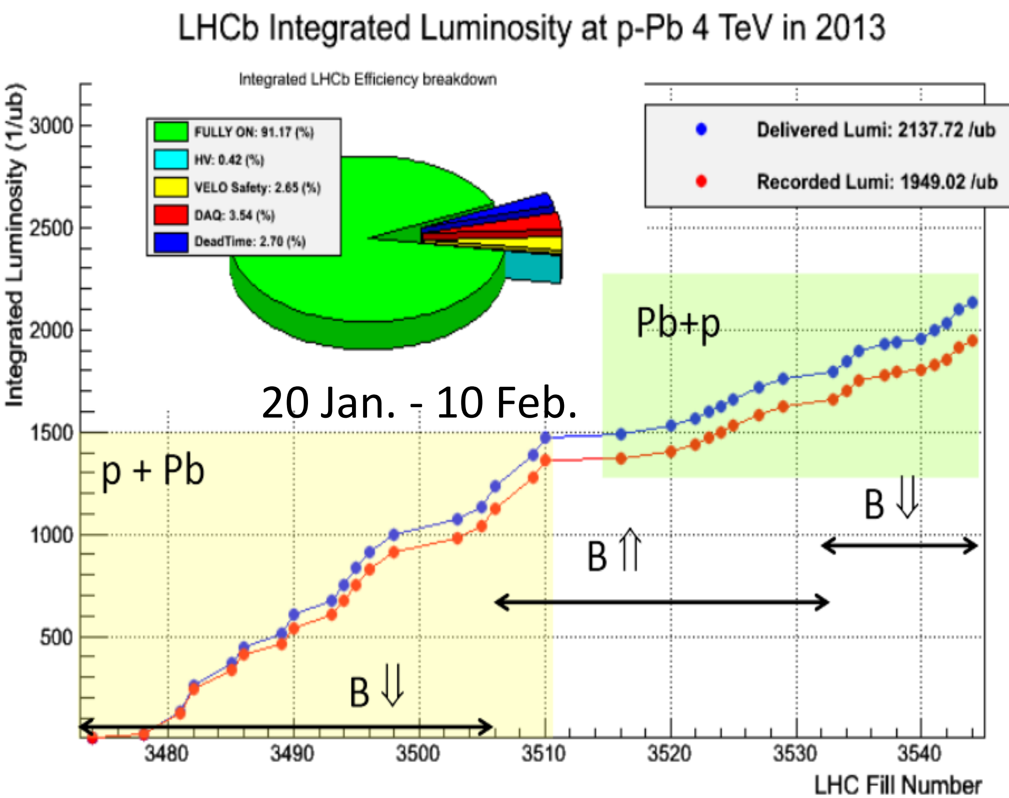
Beam configuration





- Asymmetric beam energy
  - ✓ $E_p = 4$ TeV
  - ✓ $E_N = 1.58$ TeV for lead beam
  - ✓ $\sqrt{s_{NN}} = 5$ TeV
  - ✓ rapidity shift $\Delta y = \pm 0.465$
- Rapidity coverage (in NN c.m.s. frame)
  - ✓ **Forward direction (*p*Pb)**
    $1.5 < y < 4.0$
  - ✓ **Backward direction (Pb*p*)**
    $-5.0 < y < -2.5$
- Common coverage
  - ✓ $2.5 < |y| < 4.0$

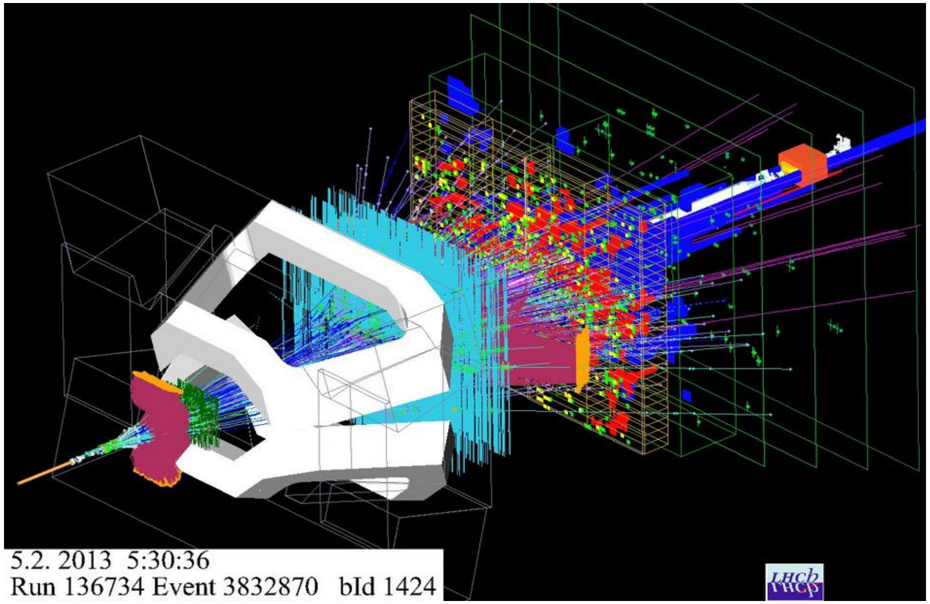
2013 pPb data taking

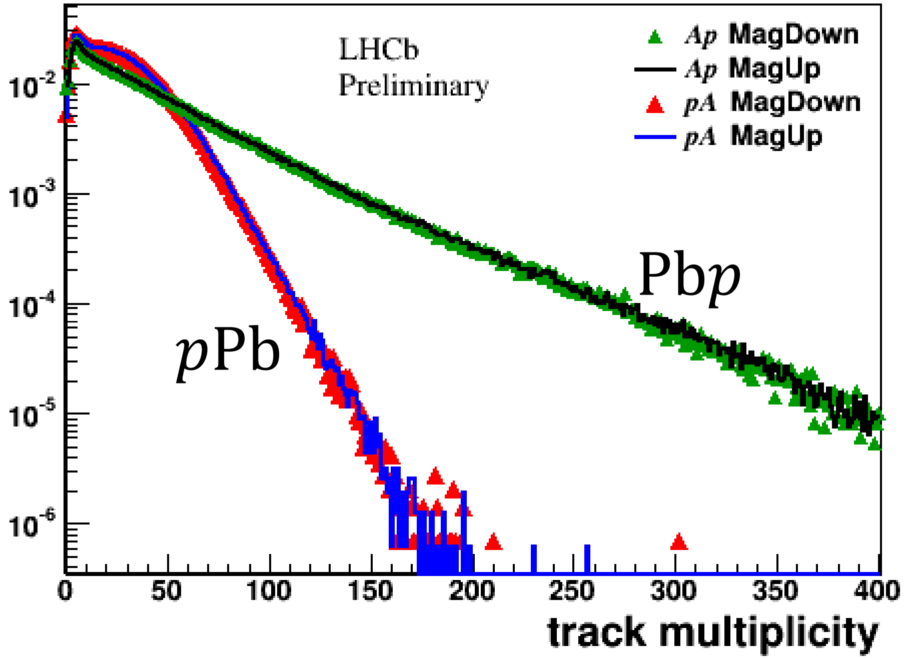


- ✓ $\sqrt{s_{NN}} = 5\ \mathrm{TeV}$
- ✓ Low instantaneous luminosity ($\sim 5 \times 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- ✓ Low pile-up
- ✓ Four configurations: pPb (Pbp), Magnet Up(Down)

Integrated luminosity after data quality:
Forward (pPb) : $1.1\ \mathrm{nb}^{-1}$
Backward (Pbp): $0.5\ \mathrm{nb}^{-1}$

Event display and track multiplicity

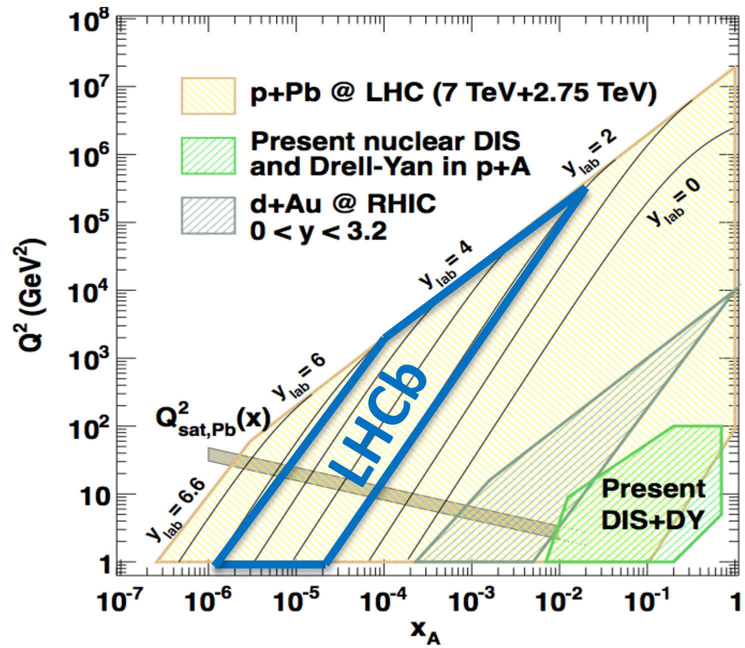




- ✓ Magnetic Up/Down agree for both pPb and Pbp
- ✓ Higher multiplicities in Pbp as expected

Physics motivation

- pA collisions are important to study cold nuclear matter effects
- Cold nuclear matter effects are of great interest by themselves, in addition to QGP studies
- Insight to unexplored region of QCD phenomena
- Constrain nuclear Parton Density Function at low x over wide Q^2



- LHCb can play an important role
- Unique rapidity coverage with full particle identification

http://cds.cern.ch/journal/CERNBulletin/2013/08/News%20Articles/1514560?ln=en

Heavy quarkonia suppression in pA

- Important probes of QGP, and also
- Sensitive to cold nuclear matter effects
  - ✓ Strongly suppressed in pA collisions at large rapidity
- Cold nuclear matter effects characterized by

Nuclear modification factor:

$$R_{pA}\left(y,\sqrt{s_{NN}}\right) = \frac{1}{A}\cdot\frac{\frac{\mathrm{d}\sigma_{pA}}{\mathrm{d}y}(y,\sqrt{s_{NN}})}{\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}y}(y,\sqrt{s_{NN}})}$$

Forward-backward production ratio:

$$R_{\mathrm{FB}}\left(y,\sqrt{s_{NN}}\right) = \frac{\sigma_{pA}\left(+|y|,\sqrt{s_{NN}}\right)}{\sigma_{pA}\left(-|y|,\sqrt{s_{NN}}\right)}$$

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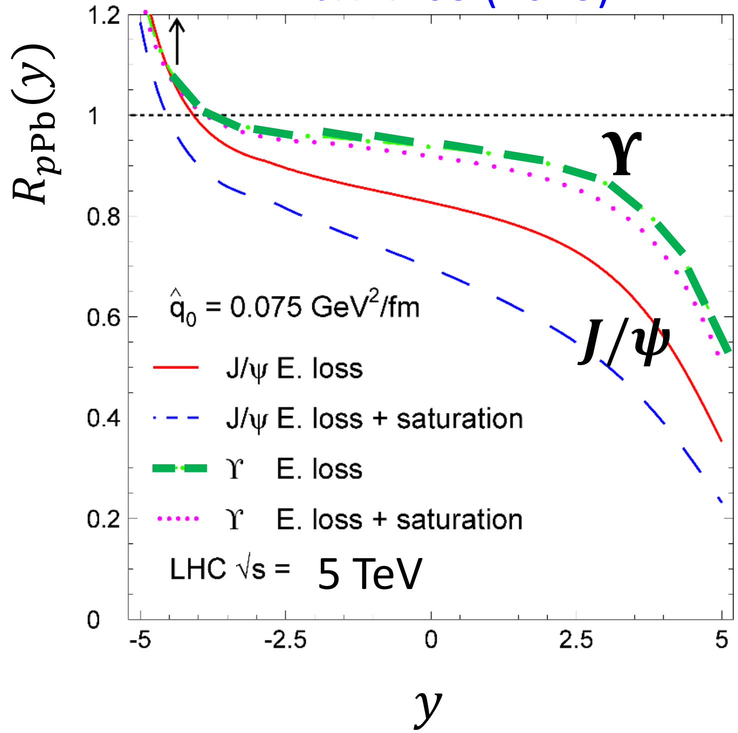


J/ψ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5\ \mathrm{TeV}$

[JHEP 02 (2014) 072]

Analysis strategy

- Reconstructed using $J/\psi \to \mu^+\mu^-$ decay channel
- Measurement performed in bins of p_T and y

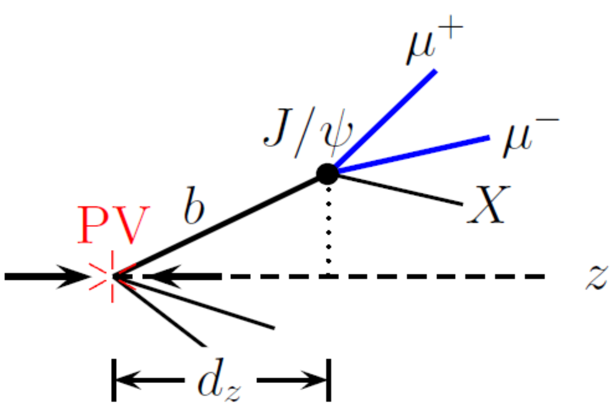
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} = \frac{N^{\mathrm{corr}}(J/\psi\to\mu^+\mu^-)\ \text{in bin of}\ (p_\mathrm{T},y)}{\mathcal{L}\times\mathcal{B}r(J/\psi\to\mu^+\mu^-)\times\Delta p_\mathrm{T}\times\Delta y}$$

- Three sources of J/ψ at hadron colliders
  - Direct J/ψ
  - Feed-down from heavier $c\bar{c}$ states
  - From b-hadron decays

Prompt J/ψ

J/ψ from b

- Prompt J/ψ and J/ψ from b separated by pseudo proper time $t_z = d_z \times \frac{M_{J/\psi}}{p_z^{J/\psi}}$



Note:
Cold nuclear matter effects on J/ψ from b reflect those on b hadrons!

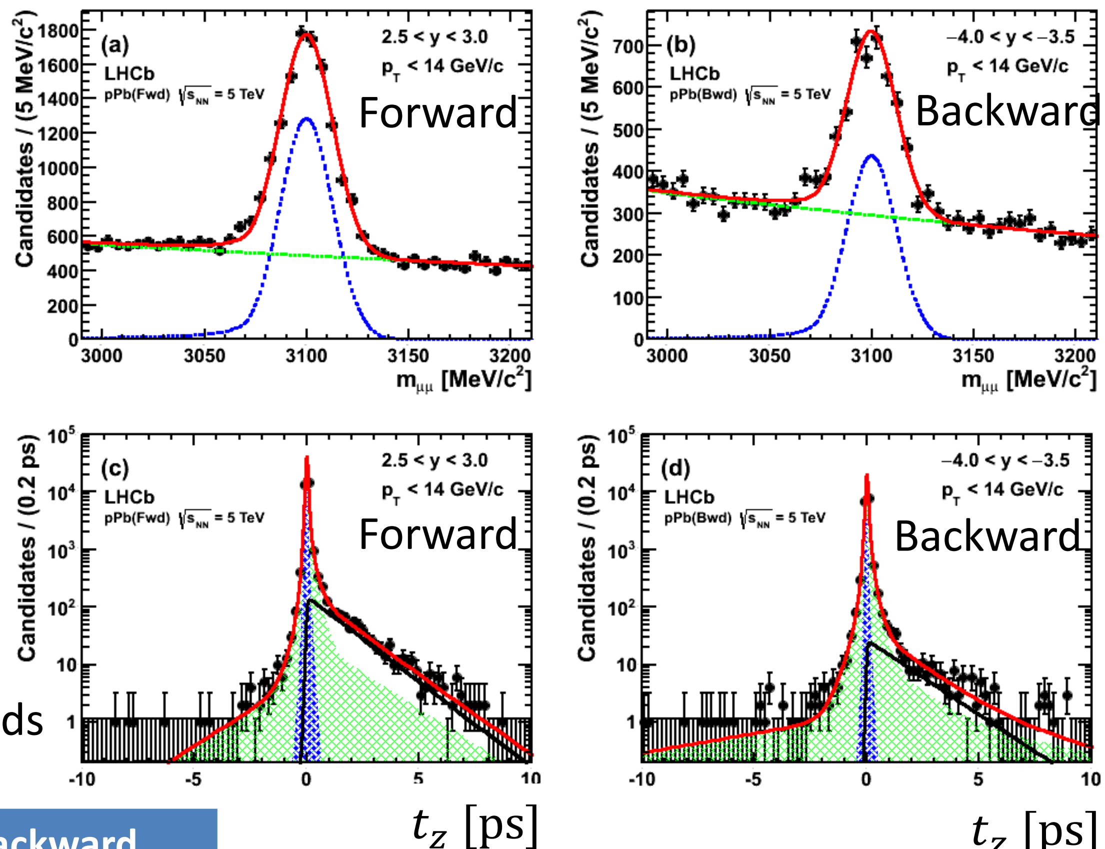
J/ψ signal extraction

JHEP 02 (2014) 072

➢ Yields of prompt J/ψ and J/ψ from b extracted in each (p_{T}, y) bin from simultaneous fit to mass and pseudo proper time t_z

- **Mass distribution**
  - ✓ Signal by Crystal Ball function
  - ✓ Background by exponential

- **t_z distribution**
  - ✓ Prompt signal
    δ-function $\otimes$ $f_{\mathbf{res}}$
  - ✓ non-prompt signal
    exponential $\otimes$ f_{res}
  - ✓ background
    empirical functions from sidebands



Sigal yield	Forward	Backward
Prompt J/ψ	$25{,}280 \pm 240$	$8{,}830 \pm 160$
J/ψ from b	$3{,}720 \pm 80$	890 ± 40

Total J/ψ cross-sections in pPb

JHEP 02 (2014) 072

$$\sigma_{\mathrm{F}}(\text{prompt } J/\psi, +1.5 < y < +4.0) = 1{,}168 \pm 15 \pm 54\ \mu\mathrm{b}$$

$$\sigma_{\mathrm{B}}(\text{prompt } J/\psi, -5.0 < y < -2.5) = 1{,}293 \pm 42 \pm 75\ \mu\mathrm{b}$$

$$\sigma_{\mathrm{F}}(J/\psi \text{ from } b, +1.5 < y < +4.0) = 166.0 \pm 4.1 \pm 8.2\ \mu\mathrm{b}$$

$$\sigma_{\mathrm{B}}(J/\psi \text{ from } b, -5.0 < y < -2.5) = 118.2 \pm 6.8 \pm 11.7\ \mu\mathrm{b}$$

$$(\, p_{\mathrm{T}} < 14\ \mathrm{GeV}/c\,)$$

Systematics dominated by
- ✓ mass fit model
- ✓ luminosity
- ✓ data-MC disagreement

Source	Forward (%)	Backward (%)
Correlated between bins		
Mass fits	2.3	3.4
Radiative tail	1.0	1.0
Muon identification	1.3	1.3
Tracking efficiency	1.5	1.5
Luminosity	1.9	2.1
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1.0	1.0
Uncorrelated between bins		
Binning	0.1 – 8.7	0.1 – 6.1
Multiplicity weight	0.1 – 3.0	0.2 – 4.3
t_z fit (*only for* J/ψ *from* b)	0.2 – 12	0.2 – 13

Single differential J/ψ cross-sections

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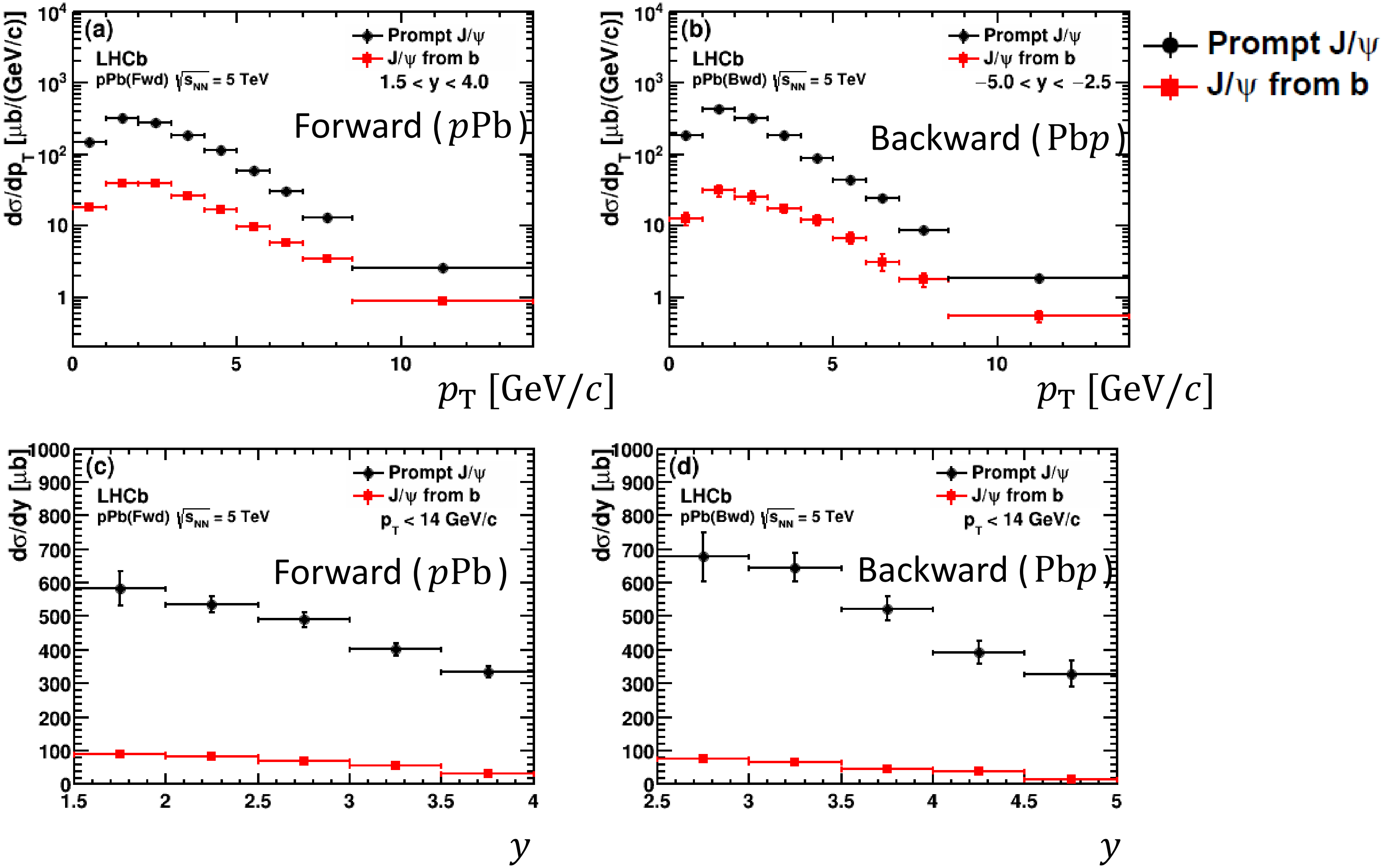

Double differential J/ψ cross-sections

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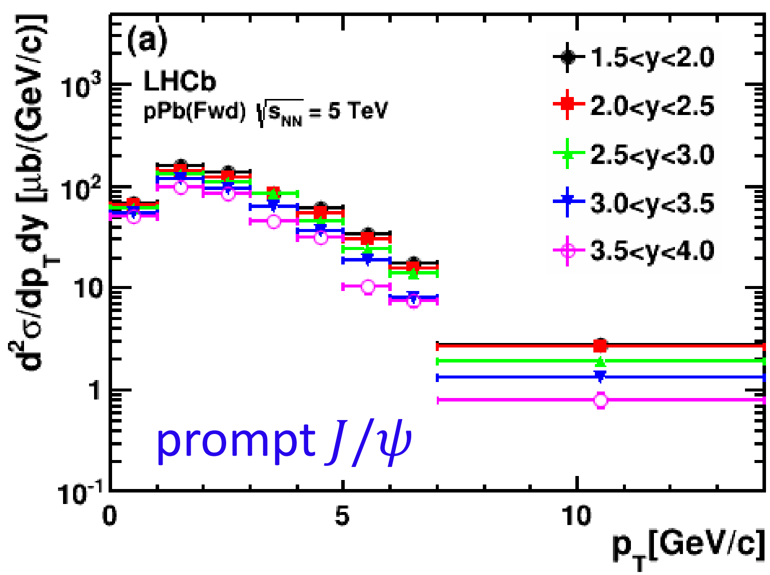
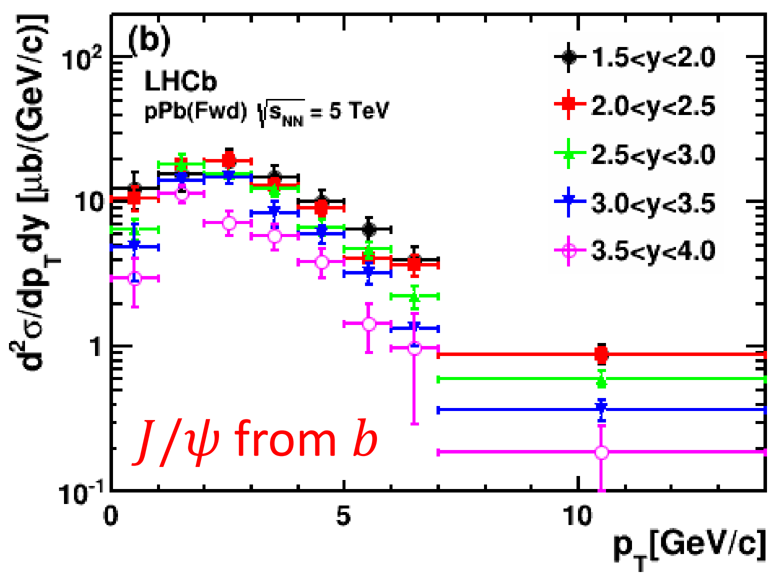
- Statistics in forward sample ($p\mathrm{Pb}$) allow measurements of double differential cross-section





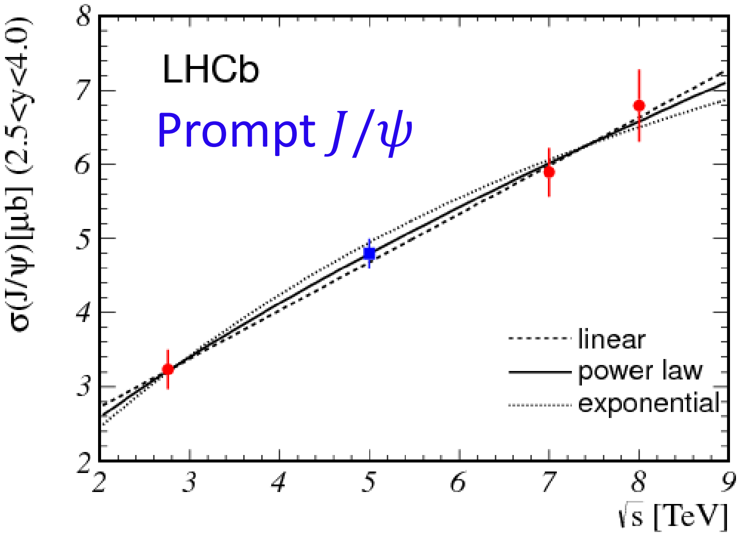
Reference cross-sections in pp at $\sqrt{s} = 5\ \mathrm{TeV}$

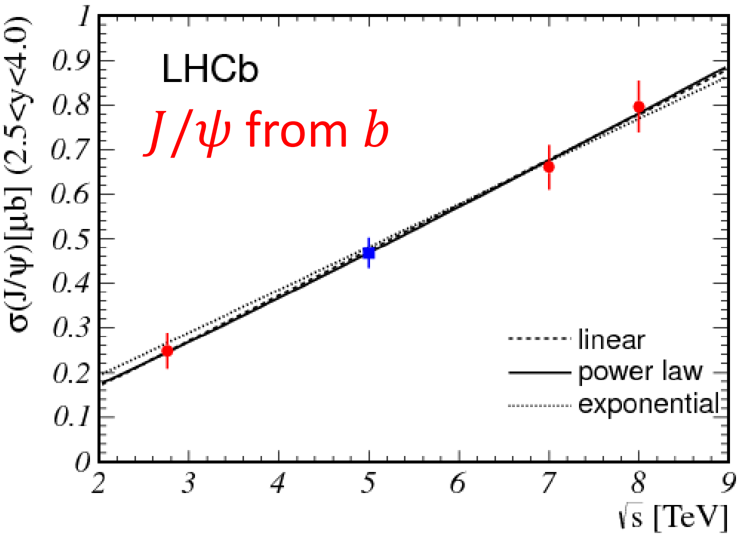
LHCb-CONF-2013-013

- Input to the determination of the nuclear modification factor $R_{p\mathrm{Pb}}$
- Interpolated from measurements at $2.76\ \mathrm{TeV}$, $7\ \mathrm{TeV}$ and $8\ \mathrm{TeV}$
- Three different fit functions used to interpolate

$$(\sqrt{s}/p_0)^{p_1} \longrightarrow \text{adopted as nominal}$$
$$p_0 + p_1\sqrt{s}$$
$$p_0\left(1 - e^{p_1\sqrt{s}}\right)$$

- Discrepancy between the three interpolated values taken as systematics
- Checked against functions from LO-CEM and FONLL





Nuclear modification factor $R_{p\mathrm{Pb}}$ for J/ψ

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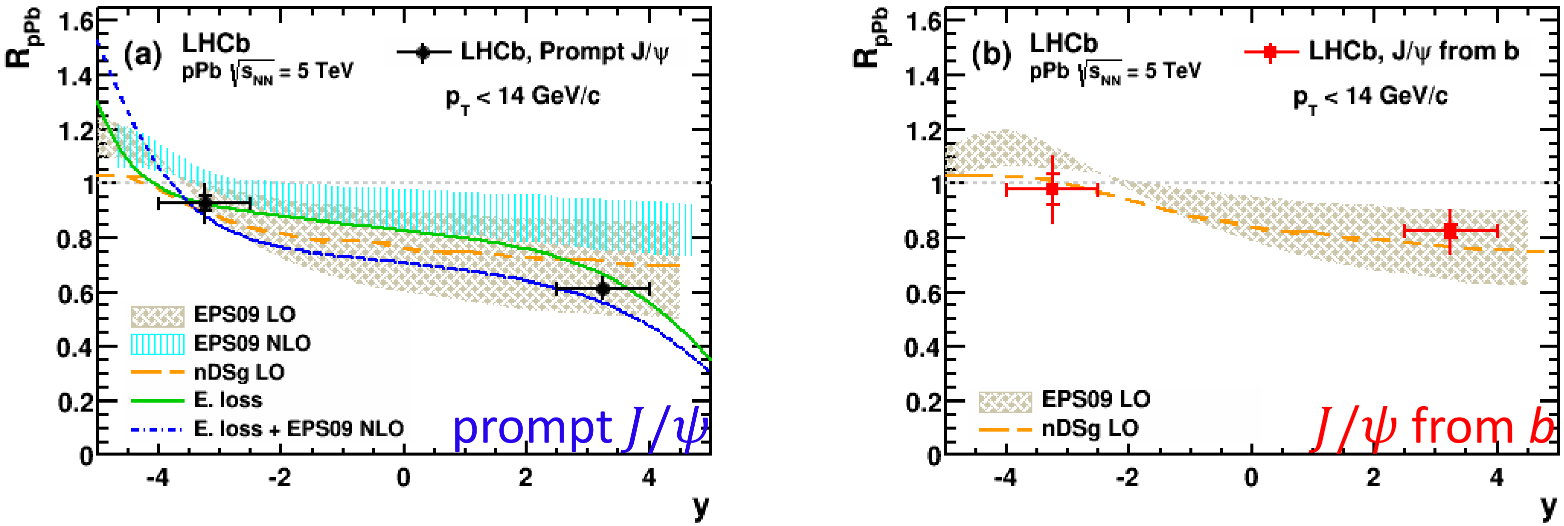
- Strong dependence on rapidity
- J/ψ form b less suppressed in forward than prompt J/ψ
  $\Rightarrow$ b hadrons less affected by cold nuclear matter effects
- Agreement with theoretical predictions
- Precision insufficient to distinguish different models



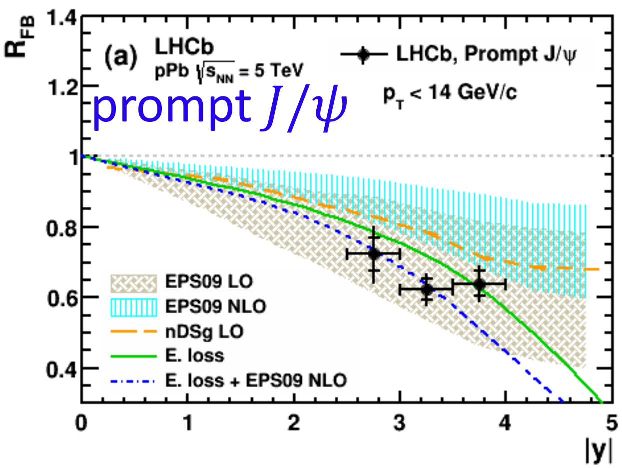
EPS09 LO — Phys. Rev. C88 (2013) 047901
EPS09 NLO — Int. J. Mod. Phys. E22 (2013) 1330007
nDSg LO — Phys. Rev. C88 (2013) 047901
E. loss — JHEP 03 (2013) 122
E. loss + EPS09 NLO — JHEP 03 (2013) 122

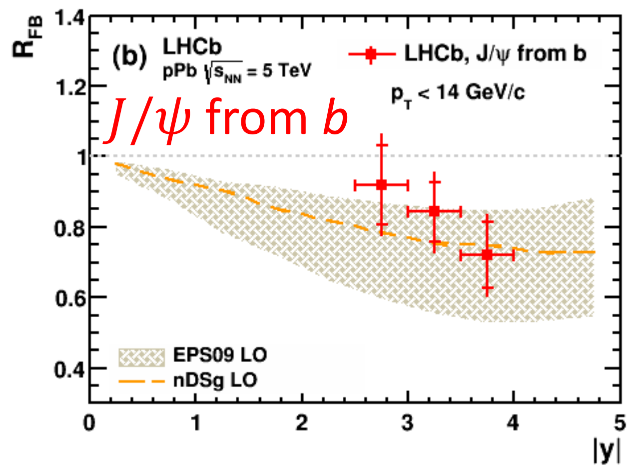
EPS09 LO
nDSg LO
arXiv:1402.1747

Forward-backward production ratio R_{FB}

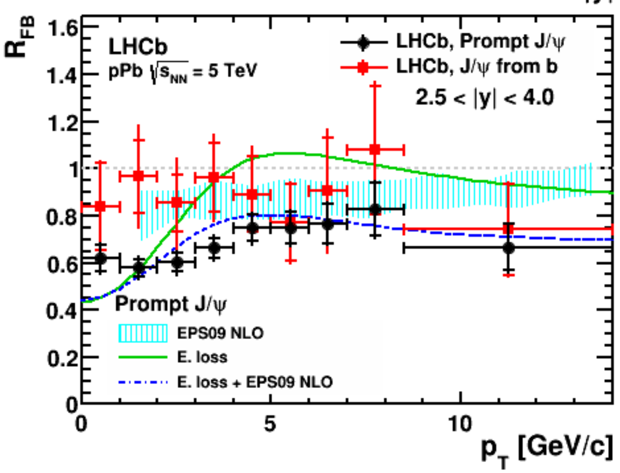
JHEP 02 (2014) 072

- Independent of pp cross-sections
- Part of experimental and theoretical uncertainties cancel
- Clear difference between prompt J/ψ and J/ψ from b





EPS09 LO
nDSg LO
arXiv:1402.1747



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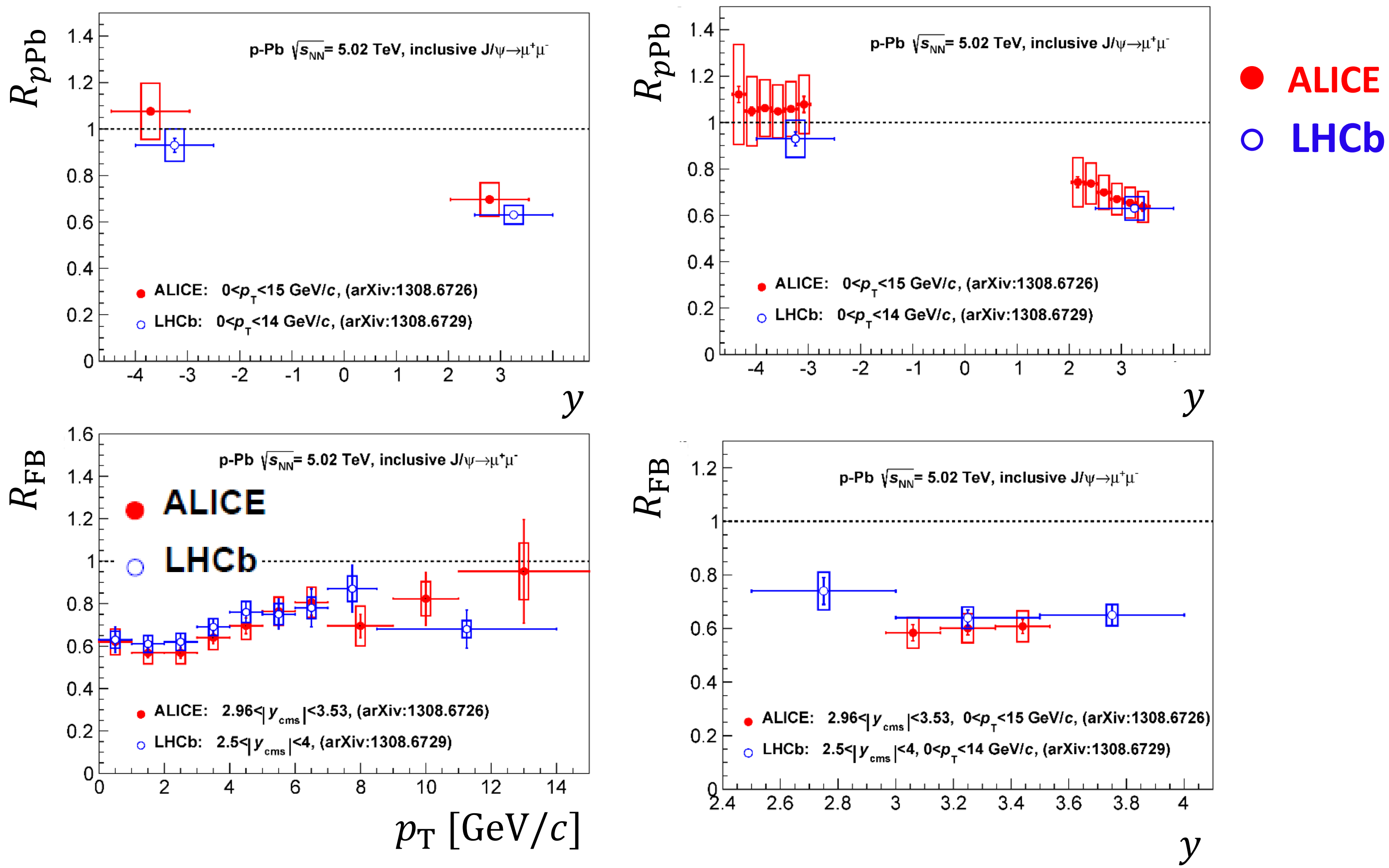
E. loss + EPS09 NLO	JHEP 03 (2013) 122

Comparison with ALICE

LHCb-CONF-2013-013



- ➢ Measurements agree with each other

Υ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV

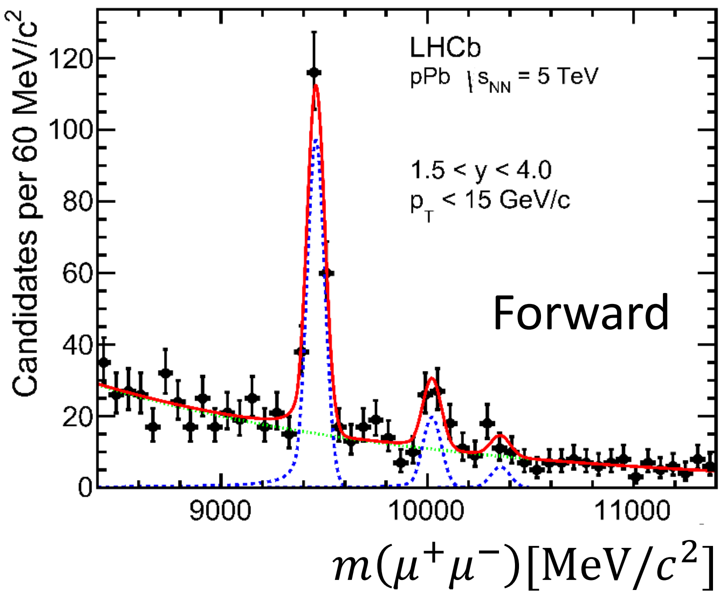
[arXiv:1405.5152]

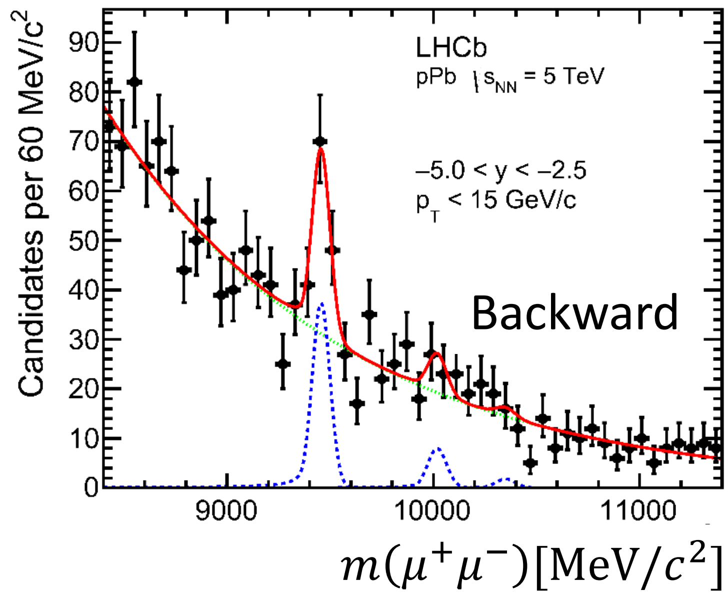
NEW!

$\Upsilon(nS)$ signal extraction

arXiv:1405.5152

- Reconstructed using $\Upsilon(nS) \to \mu^+\mu^-$ decay channel
- Signal modelled by three Crystal Ball functions
- Background modelled by exponential





Signal yield	Forward (*p*Pb)	Backward (Pb*p*)
$\Upsilon(1S)$	189 ± 16	72 ± 14
$\Upsilon(2S)$	41 ± 9	17 ± 10
$\Upsilon(3S)$	13 ± 7	4 ± 8

$\Upsilon(nS)$ cross-section in pPb

arXiv:1405.5152

- Total cross-section with $p_{\mathrm{T}} < 15\ \mathrm{GeV}/c$ measured
- Systematic uncertainty dominated by mass fit model, data-MC discrepancy, and trigger efficiency

$$\sigma(\Upsilon(1S), -5.0 < y < -2.5) \times \mathcal{B}(1S) = 295 \pm 56 \pm 29\ \mathrm{nb}$$
$$\sigma(\Upsilon(2S), -5.0 < y < -2.5) \times \mathcal{B}(2S) = 81 \pm 39 \pm 18\ \mathrm{nb}$$
$$\sigma(\Upsilon(3S), -5.0 < y < -2.5) \times \mathcal{B}(3S) = 5 \pm 26 \pm 5\ \mathrm{nb}$$
$$\sigma(\Upsilon(1S), 1.5 < y < 4.0) \times \mathcal{B}(1S) = 380 \pm 35 \pm 21\ \mathrm{nb}$$
$$\sigma(\Upsilon(2S), 1.5 < y < 4.0) \times \mathcal{B}(2S) = 75 \pm 19 \pm 5\ \mathrm{nb}$$
$$\sigma(\Upsilon(3S), 1.5 < y < 4.0) \times \mathcal{B}(3S) = 27 \pm 16 \pm 4\ \mathrm{nb}$$

- Production ratios $R^{nS/1S} \equiv \frac{\sigma(\Upsilon(nS))\times\mathcal{B}r(\Upsilon(nS)\to\mu^+\mu^-)}{\sigma(\Upsilon(1S))\times\mathcal{B}r(\Upsilon(1S)\to\mu^+\mu^-)}$ measured $(n = 2, 3)$

$$R^{2S/1S}(-5.0 < y < -2.5) = 0.28 \pm 0.14 \pm 0.05$$
$$R^{3S/1S}(-5.0 < y < -2.5) = 0.02 \pm 0.09 \pm 0.02$$
$$R^{2S/1S}(1.5 < y < 4.0) = 0.20 \pm 0.05 \pm 0.01$$
$$R^{3S/1S}(1.5 < y < 4.0) = 0.07 \pm 0.04 \pm 0.01$$

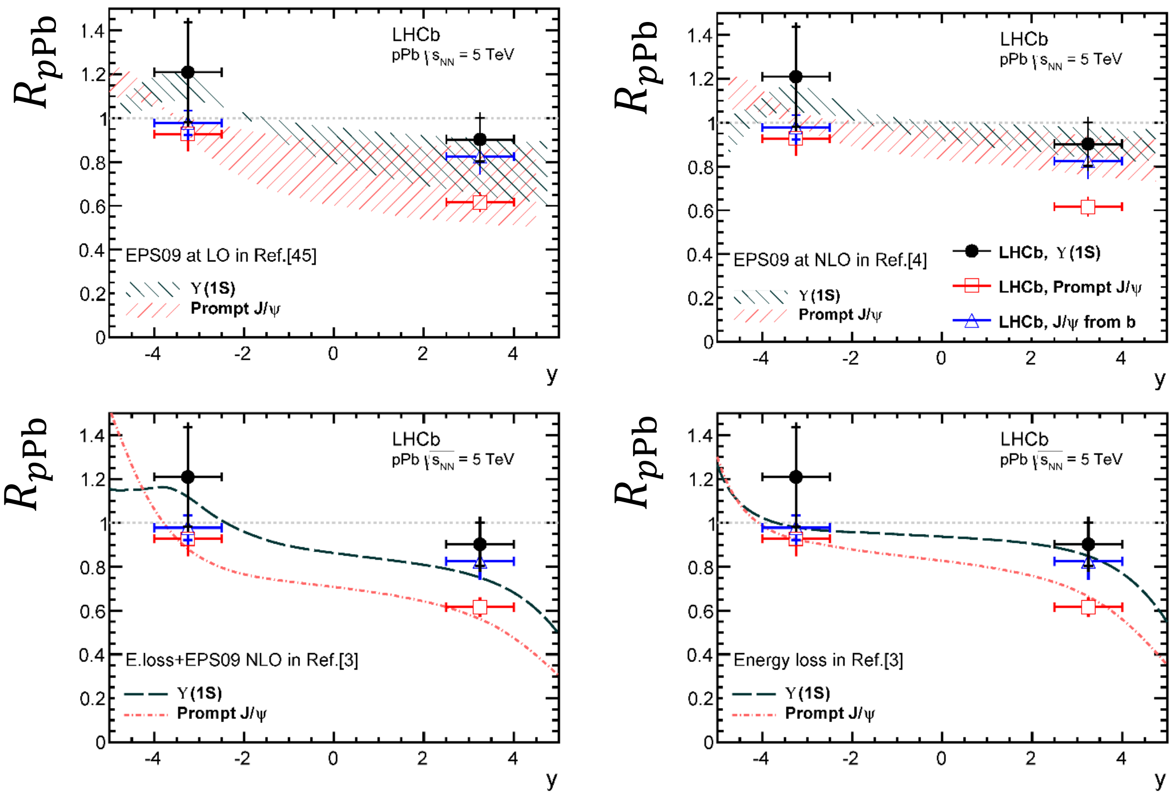
consistent with pp results but limited by statistics

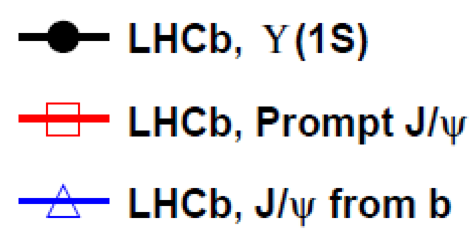
$$R^{2S/1S}(pp) \sim 0.24$$
$$R^{3S/1S}(pp) \sim 0.12$$

Nuclear modification factor for $\Upsilon(1S)$

arXiv:1405.5152

- Reference pp cross-section interpolated as done for J/ψ
- Forward region: suppression smaller than prompt J/ψ, and compatible with b hadrons
- Backward region: indication of antishadowing effect
- Consistent with different theoretical models with large uncertainty





Theoretical predictions:

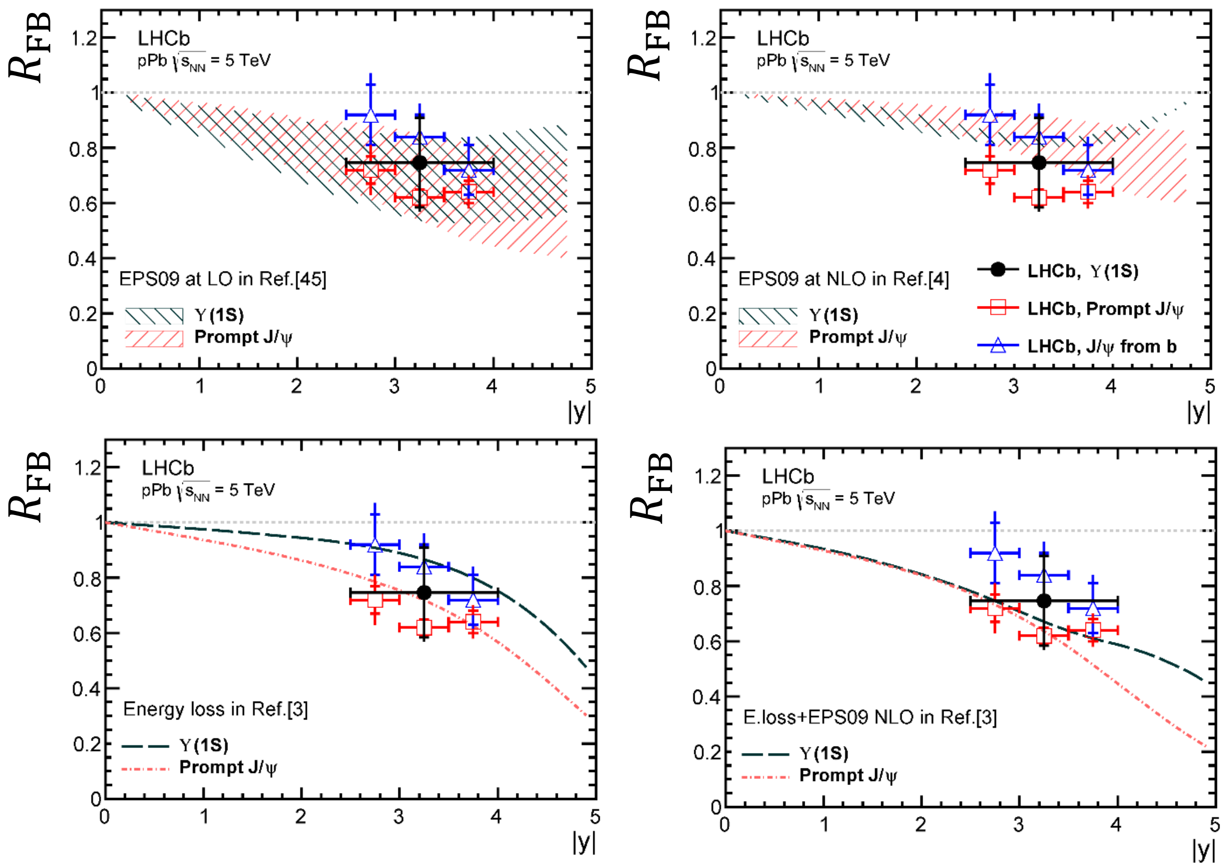
EPS09 LO : EPJC 73 (2011) 2427

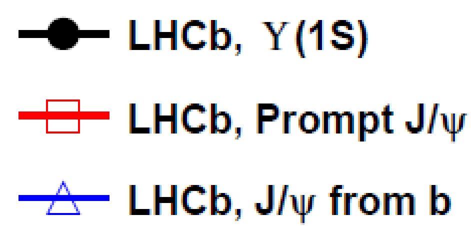
EPS09 NLO: IJMP E22 (2013) 1330007

E. loss : JHEP 03 (2013) 122

Forward-backward production ratio R_{FB} arXiv:1405.5152

- Independent of pp cross-sections
- Part of experimental and theoretical uncertainties cancel
- Agreement with different theoretical models, but statistical uncertainty large





Theoretical predictions:

EPS09 LO : EPJC 73 (2011) 2427

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E. loss : JHEP 03 (2013) 122

Summary and prospects

- Study of pA collisions is important for probing some unexplored QCD physics, and provides inputs for QGP studies
- LHCb has recorded about $1.8\ \mathrm{nb}^{-1}$ $p\mathrm{Pb}$ data in a unique kinematic range with full particle identification
- Production cross-sections measured for prompt J/ψ, J/ψ from b, and $\Upsilon(nS)$
- Nuclear modification factor $R_{p\mathrm{Pb}}$ and forward-backward production ratio R_{FB} determined for prompt J/ψ, J/ψ from b, and $\boldsymbol{\Upsilon(1S)}$
- Measurements agree with theoretical models, but power to distinguish different models is limited by statistics
- Further analyses under way, $\psi(2S)$, ridge effect, etc
- Looking forward to 10-times more integrated luminosity in Run II

Thank you!

Backup slides

Efficiency for J/ψ

- Efficienties $\epsilon_{tot} = \epsilon_{acc} \times \epsilon_{rec} \times \epsilon_{\mathrm{trig}}$ $(\sim 45\%)$
  - ✓ ϵ_{acc}: geometric acceptance
    estimated from simulation with unpolarized J/ψ
  - ✓ ϵ_{rec}: including reconstruction and selection
    estimated from simulation
  - ✓ ϵ_{trig}: trigger efficiency
    obtained from the minimum-bias sample collected in the data